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AN EVALUATION OF THE USE OF TUNABLE INFRARED SOURCES FOR AEDC SENSOR TESTING

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This report has been reviewed and approved.

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In an effort to increase the capability of infrared sensor testing at AEDC due to the requirements of advanced technology sensors, various novel, state-of-the-art infrared sources were considered as immediate supplements to or eventual replacements for existing sources. Recent and future source requirements such as sufficiently narrow linewidth, wavelength calibration accuracy, and large dynamic range of intensity cannot be met by blackbody-type sources and their attendant optics. A multiplicity of

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modern infrared radiation generation techniques exists, and two of these, the tunable diode laser and difference-frequency generation, were identified as potential short-term and long-term solutions to at least some of the new requirements. In addition, a diode laser was rented for a one-month period for an experimental evaluation of particular characteristics of importance in its proposed sensor testing application.

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PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). The Air Force project manager was Dr. H. E. Scott. The results of the research were obtained by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Project Numbers V32S-A9A and V32I-P4A. The analysis of results was completed on April 14, 1978 and the manuscript was submitted for publication on October 5, 1978.

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1.0 INTRODUCTION

Ground-based simulation of space environmental conditions for orbiting sensor testing has been performed at the Arnold Engineering Development Center (AEDC) for over ten years. The purposes of such investigations include not only the verification of operability of such sensors under space conditions but also the calibration of the sensitivity of these devices. Provision of proper test facilities is made difficult by the requirement of low spectral background environments for the infrared (IR) sensors, which operate in the 3- to 30-μm region, as well as by the required simulation of both single and multiple targets, including fixed and movable sources. Descriptions of such test facilities which have been developed and are in use at AEDC are given in Ref. 1. As described in Ref. 1, the accurate calibration of IR sensor systems requires the use of a radiation source which is capable of variation of intensity output of many orders of magnitude and, further, is both spectrally pure and tunable over the wavelength interval of interest. Additional source requirements, in general terms, include both amplitude and wavelength stability, continuous but modulatable operation, and simplicity with regard to utilization. Finally, the IR source intensity and wavelength must both be accurately known.

These requirements have been fulfilled with varying degrees of success by the use of blackbody sources, integrating spheres, and a cryogenic monochromator, all of which are located within the test facility as described in Ref. 1. If past sensor test requirements were unchanging, the existing system performance would, in all probability, be acceptable, and any modifications would be directed toward the improvement of calibration accuracy. However, sensor testing requirements are anything but static, and the demands for improved simulation and calibration testing directly reflect the enhanced performance levels of sensor systems. In this regard, known future sensor testing requirements exceed the present capabilities with regard to narrowness of linewidth, intensity variation, and source beam size. To satisfy these and other requirements significant improvements are required in the areas of beam transfer optics, multiple target sources, target velocity, and IR source capabilities. It is the area of IR source improvements to which this work is addressed. Specifically, the focal point of this study was the IR source itself, exclusive of the ancillary components which, with the IR source, comprise the IR source system; the goal was to investigate the applicability to sensor testing requirements of known alternate IR sources with the intent of improving one or more of the source requirements such as output power with its variability, tunability, spectral and amplitude stability, and linewidth. The following sections describe the results of this preliminary study.

2.0 INFRARED SOURCES FOR SENSOR TESTING

To provide the desired IR radiation, current AEDC test facilities use the thermal radiance produced by such sources as the reentrant blackbody cavity or capsule heaters of Nichrome® filaments, the selection being determined by the application desired. As described in Ref. 1, for the reentrant blackbody cavity and the capsule heater, both two and three integrating sphere assemblies are used to produce IR radiation of the desired quality and magnitude. For narrow bandwidth studies the Nichrome filament is used in conjunction with a cryogenically cooled monochromator. The scanning monochromator employed is a 0.25-m focal length instrument with an Ebert mount for the grating. For all three types of sources, required supporting apparatus includes both bandpass and order-sorting filters, apertures, choppers for modulation, and neutral density attenuation filters. An appreciation of the orders of magnitude of various quantities involved in such measurements may be gained from Fig. 1, which shows the variation with wavelength of the spectral flux density, or radiant emittance, $\hat{P}_\lambda$, for thermal radiance blackbody sources. Figure 1 shows that to provide a flux density of approximately 1 mw/cm^2 at 10 μm with a bandpass of 0.1 μm through an optical system of ten percent transmission will require a source temperature of approximately 1,000 K. For such a source,

$$\int_{1\,\mu m}^{30\,\mu m} \hat{P}_\lambda d\lambda = 5.64 \text{ w/cm}^2$$

Consequently, the optical system, monochromator, and filters must provide an IR spectral rejection ratio of approximately (5.6 w/cm^2)/(10^{-3} w/cm^2) $\approx$ 10^4. Comparable flux density values at wavelengths greater than 10 μm obviously require even higher source temperatures with a correspondingly larger IR rejection ratio required, and a ratio of 10^6 or greater is not unreasonable. Now, if variation in intensity of the narrow bandwidth ($\Delta\lambda \leq 0.1$ μm) is required one can, of course, selectively attenuate the radiation at the wavelength of interest, but this worsens an already unpleasant rejection ratio situation. Alternately, one can decrease the total radiation intensity at the output using an integrating sphere-filter combination or at the input by decreasing the source temperature. The latter method, of course, has the disadvantage of long thermal equilibration time requirements, whereas the former method requires accurate calibration of the filters, which is not trivial for the power levels of interest for this source. Additional problems with such a monochromator source include spurious radiation arising from grating ghosts and scatter from the grating surface as well as optical crosstalk between the source and sensor of the neutral density filters. One final consideration of the use of the monochromator for providing broadly tunable, narrow band IR radiation is the faithfulness of the representation of the input spectral power by the output power. Suppose $\hat{I}(\lambda)$ is defined as the power of the incident radiation per unit wavelength range at wavelength λ. Therefore, between λ and λ + dλ, the power of the source is defined as $\hat{I}(\lambda)d\lambda$. Using the usual expression for the luminosity of a spectrometer and defining S(λ) as the power transmitted by the spectrometer at λ, one finds that

$$S(\lambda) = d\,A\,(\cos i\;di)^2\,\hat{I}(\lambda)/R\,m'$$

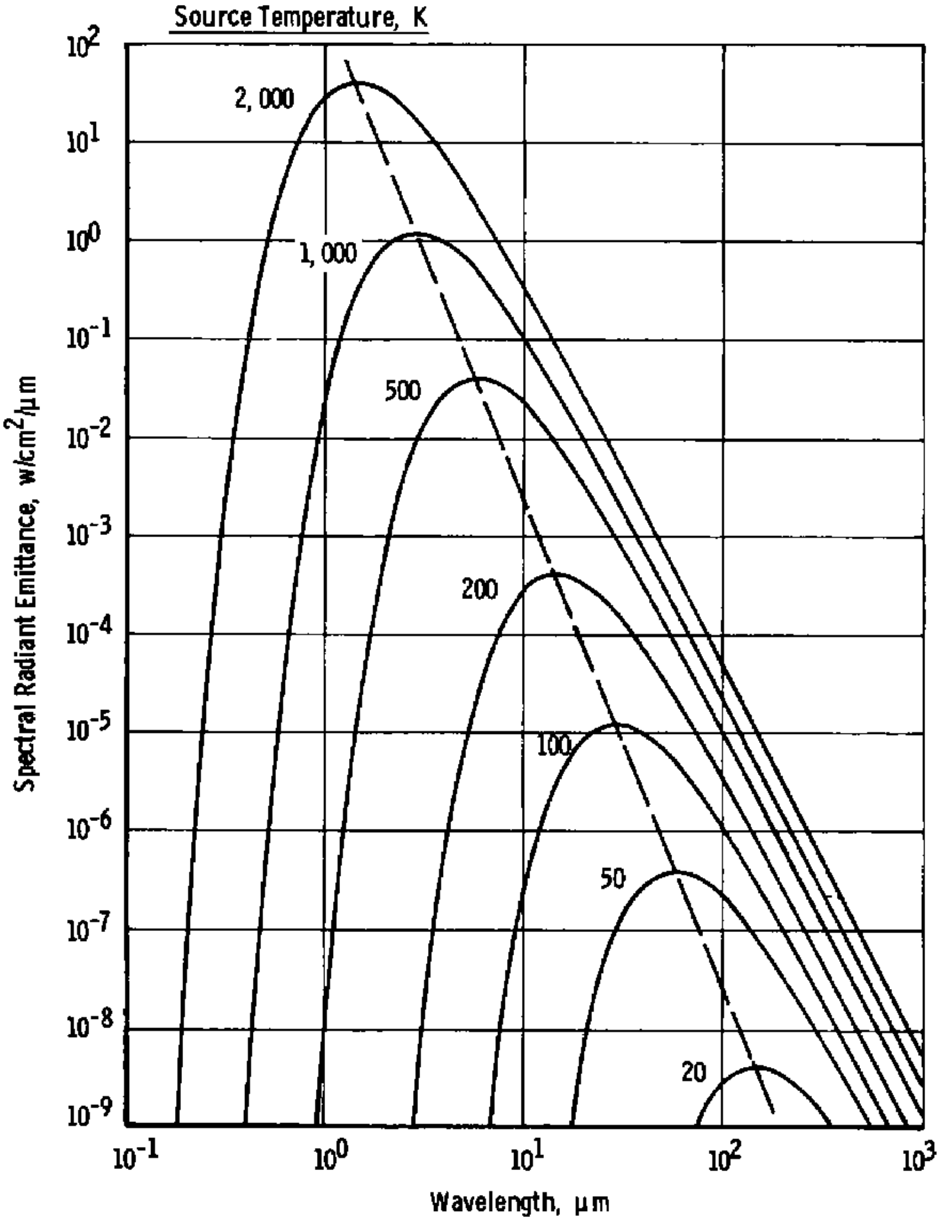


Figure 1. Spectral radiant emittance of an ideal blackbody.

where d is the grating constant, A is the grating area, m′ is the diffraction order, i is the angle of incidence, di is the equivalent slit width (in angular measure), and R is the ratio of the spectrometer focal length to slit length. Consequently, one sees that if $S(\lambda)$ is to be a faithful representation of $\hat{I}(\lambda)$ as the spectrometer scans in λ, the slit width di should vary as 1/cos i. Unfortunately, the design and operation of continuously varying, cryogenically cooled spectrometer slits are too difficult to implement; as a result, distortion occurs in $S(\lambda)$ insofar as reproducing $\hat{I}(\lambda)$ is concerned, and additional corrections are thus required.

It is quite obvious from the preceding discussion and the information in Ref. 1 that previous IR source discussion has concentrated on the narrow band, monochromator-type device, for it is believed that the greatest improvement to the IR source system can be achieved in the narrow bandwidth system, which will also serve to provide broad bandwidth scans if one desires.

Before we review alternate source characteristics, it would be helpful to specify the desired properties of an IR source for use in the testing of sensor systems. These desired properties were provided by personnel who have the responsibility of performing the sensor tests conducted at AEDC, and the properties are summarized in Table 1. Table 1 shows that the desired tunable range is from 3 to 30 μm, a range which is appropriate for known sensor systems. However, if an ideal source is to be sought which will satisfy long-range requirements, it is suggested that the upper limit be extended to no less than 100 μm and possibly somewhat longer to accomodate anticipated developments in far-infrared and submillimeter wave technology. The passband or linewidth is desired to be less than approximately 0.1-μm wavelength, and the wavelength tuning rate is desired to be on the order of 0.01 μm/sec to enable a complete 3- to 30-μm scan in times on the order of 10 minutes. Next, the output power of the source operating in a narrow linewidth mode is to be 1 mw minimum, and 10 w is estimated to be the maximum source power required for anticipated applications. Further, this power output is to be continuous rather than pulsed, but modulation capabilities are required to permit modulation of the source power over the frequency range from 10 to 500 Hz; no specifications are provided for percentage modulation desired, and it is suggested that 10- to 100-percent modulation is desired. In addition, the power output is to be capable of variation of up to ten orders of magnitude. This is to be contrasted with the existing capability of seven orders of magnitude variation for the broadband sources. Qualitatively, this variation of power should also be accomplished in times on the order of 100 to 1,000 seconds, which preclude variation of the temperature of practical thermal emittance sources due to the finite thermal equilibration times required. These preceding requirements are the result of both known and anticipated sensor testing requirements and practical considerations regarding chamber occupancy time and costs and typical test condition matrices.

Table 1. Ideal Tunable Source Requirements

Tunable Range	3 to 30 μm (3,330 to 330 cm^{-1})
Passband	≤ 0.1 μm (from 100 cm^{-1} at 3 μm to 1 cm^{-1} at 30 μm)
Wavelength Tuning Rate	0.01 μm/2 sec (330 cm^{-1}/min at 3 μm and 3.3 cm^{-1}/min at 30 μm)
Power	10^{-3} w Minimum (10 w as a Practical Maximum)
Dynamic Range	Up to 10^{10} Power Variation
Duty Cycle	CW (Continuous Wave)
Coherence and Polarization	Not Important
Collimation	Not Important
Source Thermal Temperature	Less than 20K
Source System Size	Maximum of 12 by 12 by 12 in. for AEDC Aerospace Chamber (7V)
Environmental	Toleration of 20K and 10^{-6} Torr, No Component Outgassing

The following specifications are less well defined, for they require knowledge of the type of source used, whether the source is internal or external to the test chamber, and, if external, the method of radiation injection. For example, the source thermal temperature, system size, and environmental properties are appropriate only for sources located within the cold-wall, evacuated test chamber. Although they do have limits, external sources are not so stringently restricted in these three categories. Regarding source collimation, polarization, and coherence, sensor testing personnel were not aware of any restrictions for these parameters; obviously, with a blackbody-type source there are no limits with regard to these three parameters. However, it is suggested that all three parameters might be used to advantage depending on the selected source and its location with respect to the chamber. As an example, it is obviously desirable to use an IR source external to the evacuated, cold test chamber if for no other reason than ease of operation and maintenance. However, injection of the radiation through a window which is transparent throughout the IR spectrum results in additional source background from the thermal continuum radiation. This situation can be significantly improved by using a coherent, collimated IR beam rather than the incoherent source, for then diffraction-limited optics permit the formation of a much smaller diameter beam and, therefore, a much smaller diameter window and a significantly lower thermal background. In addition, once interior to the chamber, diffraction effects can be used advantageously to further reduce the backgound, undiffracted contribution; that is, the difference in fringe visibility of the two types of radiation present can be used advantageously. For example, the input beam could be used to irradiate either an opaque disk located on the beam axis or the classic Young's double slit. In both cases, preferential on-axis transmission occurs for the coherent component of the radiation, and a cold, pick-off aperture can be used to reject the off-axis contributions.

In anticipating the result of this evaluation, namely that the desired alternate source will be a coherent radiation system, one recognizes the possibility of producing spatially nonuniform radiation as a result of interference and diffraction phenomena. Such possibilities will be most significant for such testing applications as mosaic sensors and multiple target systems. The order of magnitude appropriate to such processes is simply obtained; as an example, for a source of 0.01-μm bandwidth at $\lambda = 10\ \mu$m the longitudinal coherence length, L_ℓ, is found to be

$$L_\ell = \lambda^2/\Delta\lambda = 1 \text{ cm}$$

and the transverse coherence length, L_t, which depends on the angle θ (radian) subtended by the source, is

$$L_t = \lambda/\theta = 10^{-3}/\theta, \text{ cm}$$

For a mosaic sensor which has H as the smaller dimension of the elemental sensor, one could ask that $L_t \ll H$, which should ensure that the nonzero fringe visibility region is confined to a single elemental sensor. Obviously, calibrations of the spatial uniformity of the field must be performed, and the spatial resolution of the calibration should exceed that of the application.

3.0 CHARACTERISTICS OF RECENTLY DEVELOPED INFRARED SOURCES

A number of tunable infrared generation methods that feature narrow linewidths for use in high-resolution infrared spectroscopy have been developed since about 1970, and all are associated with laser processes. Those producing wavelengths in the 3- to 30-μm region are listed in Table 2 (Refs. 2 and 3) along with some principal characteristics. Pulsed mode sources are included even though CW operation is desired. Requirement categories that were difficult to assess individually were dynamic range, tuning rate, size, and thermal temperature. In general, for those sources pumped by lasers, an inherent dynamic range of two orders of magnitude and adequate tuning rates may be expected. As previously mentioned, for externally located laser sources such listed restrictions as size and thermal temperature may be too severe or even invalid.

Zeeman-tuned gas lasers utilize the shift in wavelength of a transition when immersed in a magnetic field. A typical system producing widely tunable, CW, monochromatic radiation must include an intracavity etalon for isolation of a single axial cavity mode, a cavity-tuning mechanism, and a large, 10-tesla (T) magnet. A narrower range of wavelengths may be obtained by operating a CO_2 laser at high pressure, in which case the rotational linewidths in a vibrational band overlap, creating a wide gain profile. Various pumping methods have been used to initiate lasing. These two types of gas laser tuning are quite restricted in tuning range and require large and expensive equipment and were deemed to be poor sensor source prospects.

Table 2. Characteristics of Infrared Generation Methods

Infrared Generation Method	Mode of Operation	Tuning Range, μm	Bandpass, μm	Power, W
Gas Laser Tuning				
1) Zeeman-Tuned	CW	3 to 9	10^{-5}	---
2) High Pressure CO_2	Pulsed	9 to 11	10^{-6}	---
Photon Mixing				
1) Two-Photon Mixer	CW	9 to 11	10^{-6}	10^{-6}
2) Four-Photon Mixer	Pulsed	2 to 25	10^{-3}	10^{-4}
Spinflip-Raman Laser				
1) CO-Pumped Crystal	CW	5 to 6.5	10^{-8}	1
2) CO_2-Pumped Crystal	Pulsed	9 to 17	10^{-3}	10^{2}
Parametric Oscillator	Pulsed	1 to 11	10^{-5} to 10^{-2}	10^{2} to 10^{4}
Difference-Frequency Generator				
1) CW: $LiNbO_3$ Crystal	CW	2 to 4	10^{-6}	10^{-6}
2) Pulsed: Many Crystals	Pulsed	1 to 24	10^{-4} to 10^{-1}	10^{-4} to 10^{3}
Semiconductor Diode Laser	CW	1 to 34	10^{-7}	10^{-3}

The two-photon mixer combines light from a carbon dioxide laser with millimeter waves from a tunable klystron in a gallium-arsenide-loaded waveguide, generating sum and difference frequencies continuously tunable throughout the CO_2 laser's usual 9- to 11-μm discrete range. This range is too restricted for AEDC use. Four-wave mixing, in which radiation from two pulsed dye lasers is mixed in alkali metal vapors such as cesium and potassium, does produce continuously tunable infrared radiation over a large range, but unfortunately is not CW.

Spinflip-Raman lasers utilize a semiconductor crystal in a magnetic field and a CW or pulsed pump laser. In the process, crystal electrons Raman-scatter incident photons, and the laser output frequency is a function of the strength of the variable magnetic field. Again, the current tuning range is too restricted.

Interaction of laser photons with a nonlinear crystal may, with satisfaction of a number of conditions, produce coherent infrared radiation collinear with the pump laser. This process, called optical parametric oscillation, has been most successful in the pulsed mode, and an elaboration of its properties, as shown in Table 2, is given in Table 3. The output radiation is tuned by crystal rotation, temperature variation of the crystal, or immersion in an electric field, or by applying pressure. To date, continuous wave operation has been achieved only in the near infrared.

Table 3. Parametric Oscillator Characteristics

Crystal	Pump Laser	Mode of Operation	Tuning Range, μm	Bandpass, μm	Power, w
$LiNbO_3$	Nd:YAG	Pulsed	1 to 4.4	10^{-5}	10^4
$LiIO_3$	Ruby		1 to 5.5	---	10^3
Ag_3AsS_3	$Nd:CaWO_4$		1.2 to 8.5	10^{-2}	10^2
CdSe	CaF_2:Dy		3.4 to 7.9	---	10^4
CdSe	Nd:YAG		9.6 to 11	---	10^3

A multitude of configurations for the generation of infrared by difference-frequency mixing have developed and are summarized in Table 4. Beams from two visible or near-infrared lasers, at least one of which is tunable, are directed upon a nonlinear optical crystal; upon proper crystal orientation, electromagnetic wave phase matching, and focusing, a narrow-linewidth infrared beam of frequency equal to the difference of the two pump beams' frequencies may be obtained. The crystal must be transparent to the input and output beams, must have adequate birefringence for phase matching, and must mechanically

Table 4. Difference-Frequency Generator Characteristics

Crystal	Pump Lasers	Mode of Operation	Tuning Range, μm	Bandpass, μm	Power, w
$LiIO_3$	Two Dye	Pulsed	1.5 to 4.8	10^{-3}	1
$LiIO_3$	Nd:YAG and Dye		3.4 to 5.6	10^{-4}	1
$LiIO_3$	Ruby and Dye		4.1 to 5.2	---	10^2
$LiNbO_3$	Argon Ion and Dye	CW	2.2 to 4.2	10^{-6}	10^{-6}
$LiNbO_3$	Ruby and Dye	Pulsed	3 to 4	10^{-2}	10^3
Ag_3AsS_3	Ruby and Dye		3.2 to 6.5	---	10^2
Ag_3AsS_3	Ruby and Dye		6.7 to 10.5	10^{-1}	10^1
Ag_3AsS_3	Ruby and Dye		10.1 to 12.7	---	10^{-1}
Ag_3AsS_3	Dye and Dye		11 to 23	---	1
$AgGaS_2$	Ruby and Dye		4.6 to 12	---	10^{-1}
$AgGaS_2$	Two Dye		8.7 to 11.6	---	10^{-4}
$AgGaSe_2$	$LiNbO_3$ Parametric Oscillator and Nd:YAG		7 to 13	---	---
GaSe	Ruby and Dye		9.5 to 17	10^{-2}	10^2
CdSe	Two Ag_3AsS_3 Parametric Oscillators		9.5 to 24	---	1

withstand the incident photon flux. It is believed that, although little has been accomplished for CW operation, this method has potential to best provide the ideal AEDC source characteristics. The characteristics listed in Table 5 are thought to be feasible, given sufficient development effort.

Table 5. Potential Difference-Frequency Generator Characteristics

Crystal	1. $LiNbO_3$	2. Ag_3AsS_3	3. CdSe
Tunable Range	1. 1 to 5 μm	2. 1 to 20 μm	3. 1 to 30 μm
Burn or Damage Threshold	1. 50 Mw/cm^2	2. 10 Mw/cm^2	3. 60 Mw/cm^2
Tuning Method	Vary Wavelength of Visible, Tunable Dye Laser		
Passband	Typically $0.001 \leq \Delta\lambda \leq 0.1$ μm		
Wavelength Tuning Rate	Unknown but Would Easily Meet Requirement		
Power	Approximately 1 mw CW		
Dynamic Range	$\geq 10^6$		
Duty Cycle	CW		
Wavlength Calibration	Infrared Wavelength Defined by Visible Wavelength Inputs		

Some additional characteristics of semiconductor lasers are presented in Table 6, derived from specifications of Laser Analytics, Inc. Specification of the infrared output wavelength is accomplished by the choice of lead-salt alloy crystal elements and the relative concentration of each. A crystal is multilayered, of stripe geometry, and has parallel end faces that form the resonant cavity as illustrated in Fig. 2 (Ref. 4). The emittance area is typically 10 by 50 μm; the crystal face area is about 200 by 300 μm, and its length is 1 mm or less. A diode is mounted upon a metallic heat sink for operation at cryogenic temperatures of 10 to 100 K. Upon activation by a current (DC) of two amperes or less at a small fraction of a volt, the diode emits incoherent, spontaneous infrared radiation whose wavelength, λ, is determined by the bandgap energy, E, through the relation $\lambda = hc/E$. Narrow linewidth laser action occurs within the spontaneous wavelength band in one or more simultaneously emitting, longitudinal cavity modes whose wavelengths, λ_m, are given by the relation $\lambda_m = 2n\ell/m$, where n is the index of refraction, ℓ is the cavity length, and m is the number of half-wavelengths within the cavity length. A broadly diverging laser beam of long coherence length is emitted. The infrared wavelength is determined by the bandgap of the semiconductor, which is a function of the crystal temperature; fine tuning is accomplished by variation of the current through Joule heating, and coarse tuning is effected by variation of the heat sink temperature. As the current is increased, the laser frequencies decrease since the energy gap is increased. Typically, several modes, each separated by approximately 1 cm^{-1} (10^{-2} μm at 10 μm), are simultaneously emitting so that a total bandpass of about 0.1 μm exists. In the usual practice in which only one mode at a time is utilized for its very narrow linewidth, a

Table 6. Semiconductor Diode Laser Characteristics

Material Type	Composition Range	Structure	Total Tuning Range for Material Type	Approximate Tuning Range for an Individual Diode	Approximate Number of Diodes Required to Cover Total Tuning Range
$Pb_{1-x}Cd_xS$	$0 \leq x \leq 0.058$	Homostructure	2.5 to 4.4 µm (4,000 to 2,295 cm^{-1})	100 cm^{-1} (from 0.06 to 0.18 µm)	17
$Pb_{1-x}Ge_xTe$	$0 \leq x \leq 0.05$	Homostructure	4.4 to 6.5 µm (2,270 to 1,540 cm^{-1})	100 cm^{-1} (from 0.20 to 0.40 µm)	7
$PbS_{1-x}Se_x$	$0 \leq x \leq 1$	Homostructure	4.4 to 8.4 µm (2,295 to 1,190 cm^{-1})	100 cm^{-1} (from 0.20 to 0.65 µm)	11
$Pb_{1-x}Sn_xTe$	$0 \leq x \leq 0.32$	Homostructure	6.5 to 32 µm (1,540 to 312 cm^{-1})	100 cm^{-1} (from 0.45 to 7.8 µm)	12
$Pb_{1-x}Sn_xSe$	$0 \leq x \leq 0.10$	Homostructure	8.4 to 32 µm (1,190 to 312 cm^{-1})	100 cm^{-1} (from 0.77 to 7.8 µm)	9
$PbS_{1-x}Se_x$	$0 \leq x \leq 1$	Compositional Interdiffusion Heterostructure	For x = 0.2, 4.1 to 4.8 µm (2,460 to 2,060 cm^{-1})	300 cm^{-1} (0.6 µm)	1
$Pb_{1-x}Sn_xSe$	$0 \leq x \leq 0.21$	Compositional Interdiffusion Heterostructure	7.2 to 30.2 µm (1,396 to 331 cm^{-1})	300 cm^{-1} (from 2.0 to 14.4 µm)	4
$Pb_{1-x}Sn_xSe$	$x = 0.066$	Liquid Phase Epitaxy Heterostructure	11.1 to 17.1 µm (903 to 584 cm^{-1})	300 cm^{-1} (5.7 µm)	1

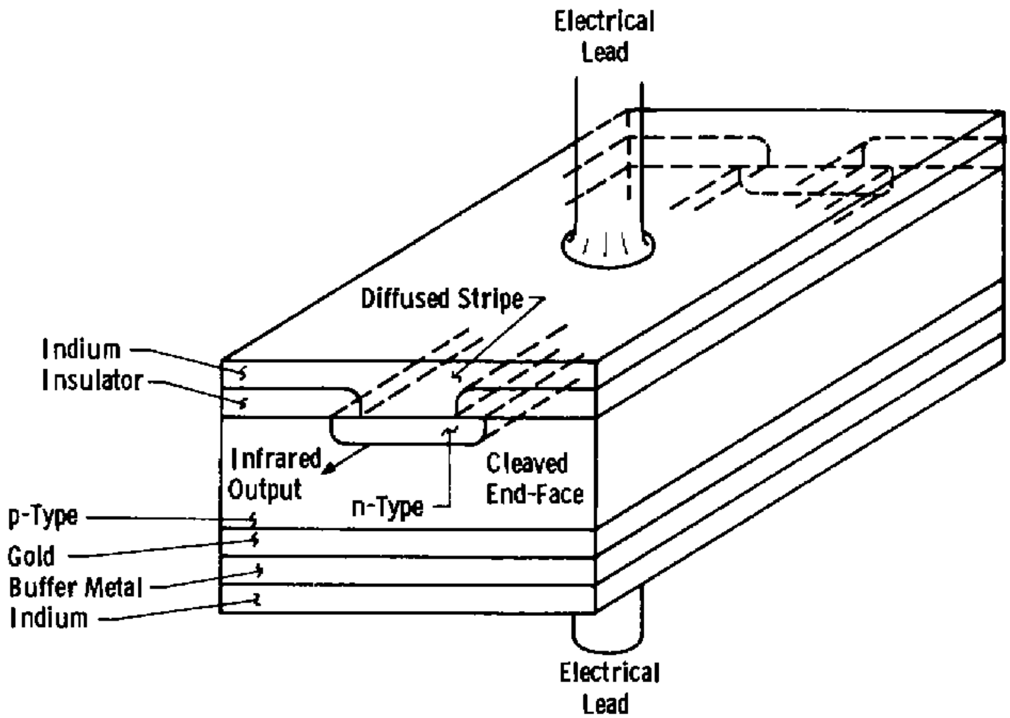


Figure 2. Schematic diagram of a diode laser.

series of different modes must be selected to cover the entire range since each mode may be current-tuned over approximately 1 cm^{-1} only. This is a result of different tuning rates between the cavity modes and the energy gap, which primarily determines the wavelength. Discontinuous frequency jumps, or mode-hopping, occurs during tuning, and the corresponding wavelength gap in which no emission occurs may be as large as the tuning range of a mode. These gaps may be at least partially filled, however, by the combination of temperature and current tuning. For a homostructure diode laser of 100 cm^{-1} extent, some 100 modes as selected by certain combinations of current and heat sink temperature would be needed. Alternately, nearly the entire range could be covered by multimode operation in which the current is fixed and the heat sink temperature is varied through its limits. Concerning sensor testing applications, diode lasers are delightfully compact and satisfy most of the ideal requirements. However, two serious disadvantages exist: (a) the diode has no inherent dynamic range in its output power; and (b) approximately 20 diodes are required to cover the entire 3- to 30-μm range.

4.0 EXPERIMENTAL EVALUATION OF A TUNABLE DIODE LASER

After the various infrared sources had been studied, it was evident that the only source capable of providing at least some of the advanced requirements in support of AEDC sensor testing in the immediate future was the tunable diode laser. However, it was difficult to determine from the literature several operating characteristics of the diode lasers which were important for this application. Included in this group of characteristics were wavelength stability, repeatability, tuning rate, and calibration accuracy, as well as power amplitude stability, repeatability, and distribution as a function of wavelength. To determine first hand these operational parameters and simultaneously gain experience with a diode laser system it was decided to rent such a device. Consequently, with the cooperation of Laser Analytics, Inc., which at that time was the only known manufacturer of widely tunable, heterostructure diode lasers, a one-month rental agreement was arranged. The following components of the Laser Analytics, Inc. system were acquired: Model SDL-3 widely tunable diode laser specified for the 7- to 8-μm wavelength range; Model TCR stable temperature, closed-cycle refrigerator system, including a stabilized, vibration-isolated cold head and helium compressor unit; Model CTS cryogenic temperature stabilizer; Model LCM laser control module; Model DLD lens doublet assembly; and interconnecting lines and cables. This equipment, whose specifications are presented in Table 7, generated a multimode, collimated or focused infrared beam. No AEDC dispersing device was available to permit isolation of single modes or to spectrally scan the emission mode structure at various conditions. Prior to arrival of this equipment, a pyroelectric detector with a Ge-coated window and an HgCdTe detector with an Irtran® II window were located and checked out with a commercial blackbody source. The HgCdTe detector's built-in dewar apparently leaked, and a cold finger supplied by liquid nitrogen from a cup-sized reservoir was fabricated for 77-K operation. A photograph and schematic diagram of the equipment are presented in Figs. 3 and 4, respectively. The interior of the cold head, seen more closely in Fig. 5, was evacuated to a pressure of one millitorr and then sealed for operation.

The diode laser temperature was controlled manually with the set point silicon sensor voltage as displayed on the Model CTS digital voltmeter, and the existing sensor voltage automatically changed to the set point voltage at a rate determined by the reset time constant and gain. A plot of the calibration of the sensor voltage as a function of temperature as performed by the manufacturer is given in Fig. 6. The manufacturer also supplied spectral scans, shown in Fig. 7, of the diode laser emission at 2.0 amperes (amp) for various temperatures, and the average mode output frequency as a function of temperature is also plotted in Fig. 6. From these data, the output frequency at 2.0 amp as a function of sensor voltage was obtained and is shown in Fig. 8. Of special interest in Fig. 7 are the emisson mode structures at the various temperatures. From two to twelve principal modes may be simultaneously emitting over a bandpass of from 5 cm^{-1} (0.024 μm) at 7.0 μm wavelength to 24 cm^{-1} (0.15 μm) at 8.0 μm wavelength. The total mode power and threshold current, I_t, at which normal emission begins are listed in Fig. 7 for each temperature.

Table 7. Laser Analytics, Inc. Instrumentation Features and Specifications

Model SDL-3 Widely Tunable Diode Laser

PbSnSe Heterostructure, Stripe Geometry
Spectral Coverage: 1,214 to 1,433 cm^{-1} (8.24 to 6.98 μm)
Temperature Range: 11.5 to 80 K
Maximum Operating Temperature: 80 K
Maximum Bias Current: 2,000 mA
Threshold Current near 10 K: 430 mA
Threshold Frequency near 10 K: 1,222 cm^{-1}

Model TCR Stable Temperature Closed Cycle Refrigerator with Model C Cryogenic Temperature Stabilizer

Temperature Range: 12 to 373 K
One-Hour Temperature Stability: ±0.001 K below 25K, ±0.003 K above 25 K
Load Capacity: 1 watt at 20 K
Cooldown Time: 90 min
Resetability: 0.003 K below 25 K
Accommodates Two Diode Lasers
CTS Temperature Sensor: Silicon Diode, Calibrated from 10 to 100 K
Temperature Set Point: Coarse and Fine Adjustments, Digital Readout
Reset Time Constant: 0.25 to 2.5 sec Adjustable
KRS-5 Window Diameter: 2.54 cm

Model LCM Laser Control Module

Stable DC Current to ±2.0000 amp
Internal and External Modulation
Low Ripple and Noise
Laser Protection Circuits
Digital Readout of Current
Waveform Available: ± Sawtooth, Triangular
Waveform Frequency: 50 Hz to 1 kHz
Waveform amplitude: 0 to 200 mA
Chopped Mode Frequency: 50 Hz to 1 kHz
Automatic Sweep Range: ±200 mA
Automatic Sweep Rate: 0.01 to 10 mA/sec

Model DLD Lens Doublet Assembly

F-Number: ~f/1.5
Focal Length: 3.8 cm
Mounted on XYZ Positioner

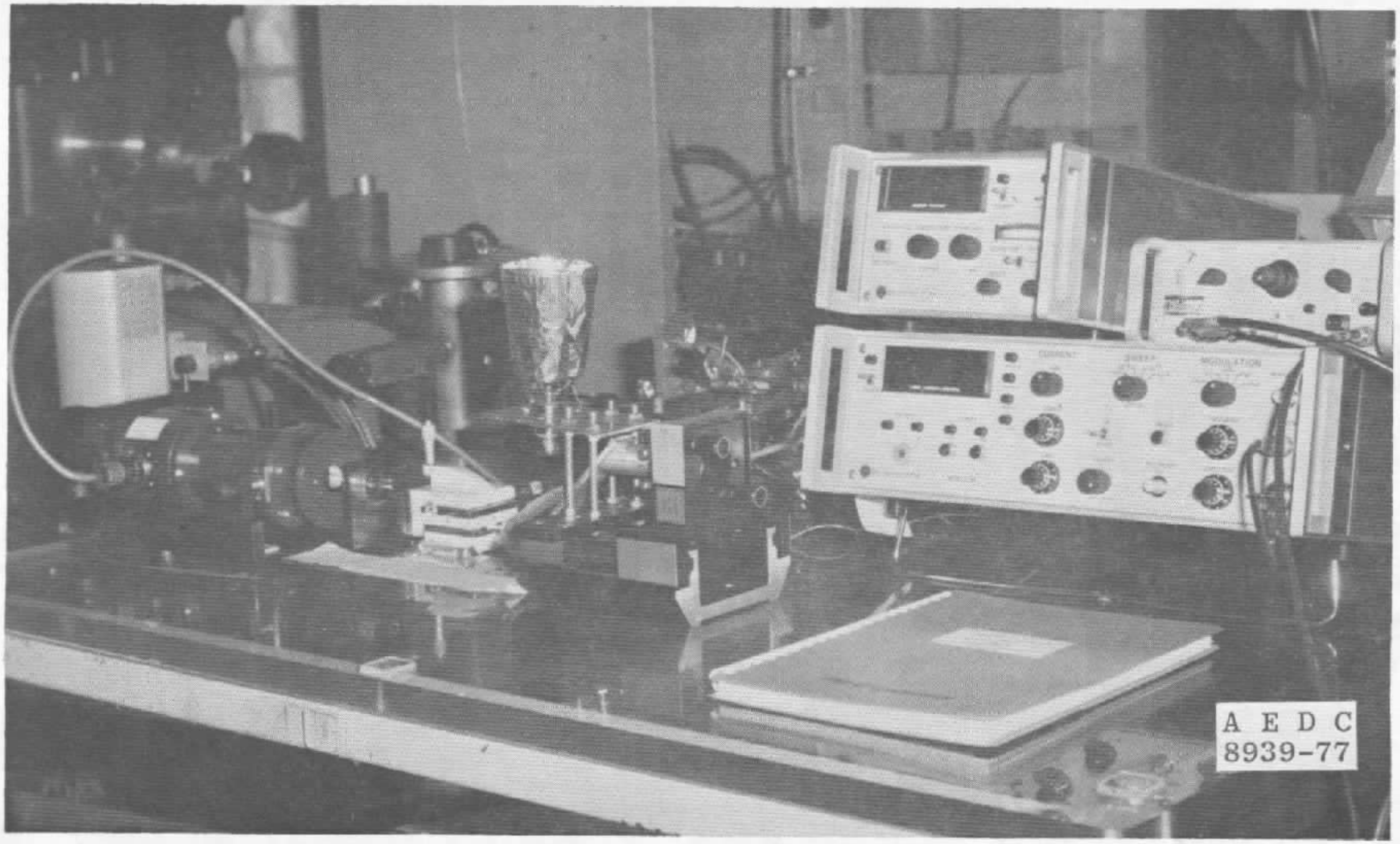


Figure 3. Photograph of experimental arrangement for evaluation of a tunable diode laser.

1. Cold Head
2. Vibration Isolation Mount
3. Diode Laser Location
4. Focusing Lens Location
5. XYZ Positioner
6. Methane Absorption Cell
7. Mirror
8. HgCdTe Detector
9. Liquid Nitrogen Dewar
10. Pitch-Yaw Mirror Control
11. Helium Compressor
12. Laser Control Module
13. Cryogenic Temperature Stabilizer
14. Detector Preamplifier
15. Oscilloscope

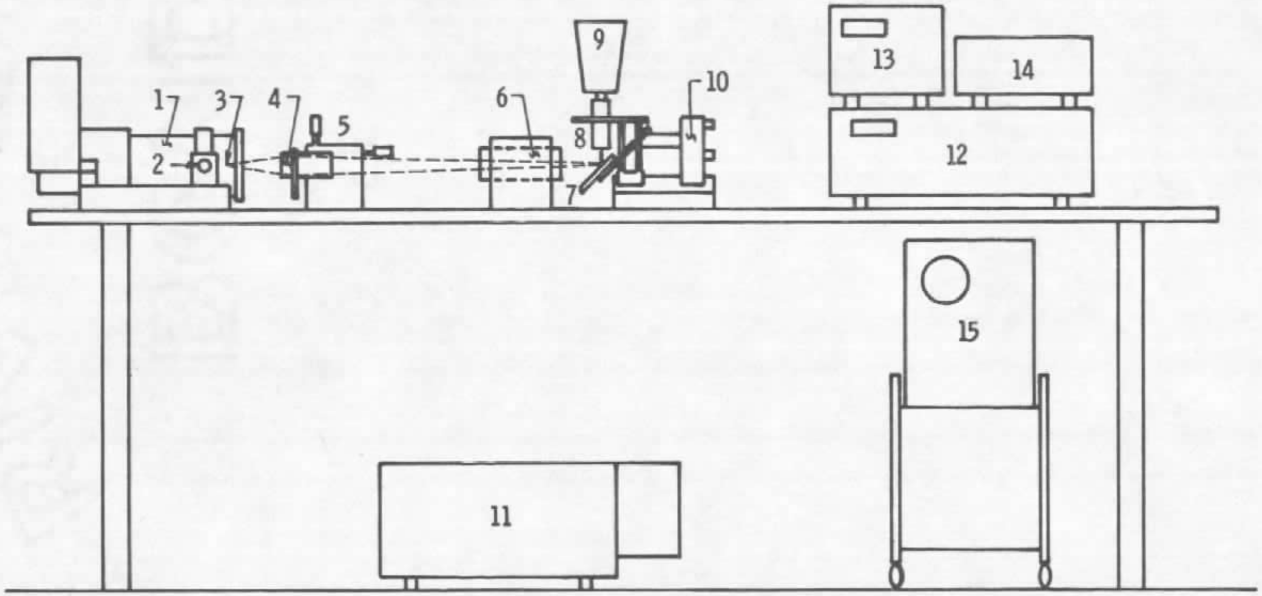


Figure 4. Schematic diagram of experimental arrangement for diode laser evaluation.

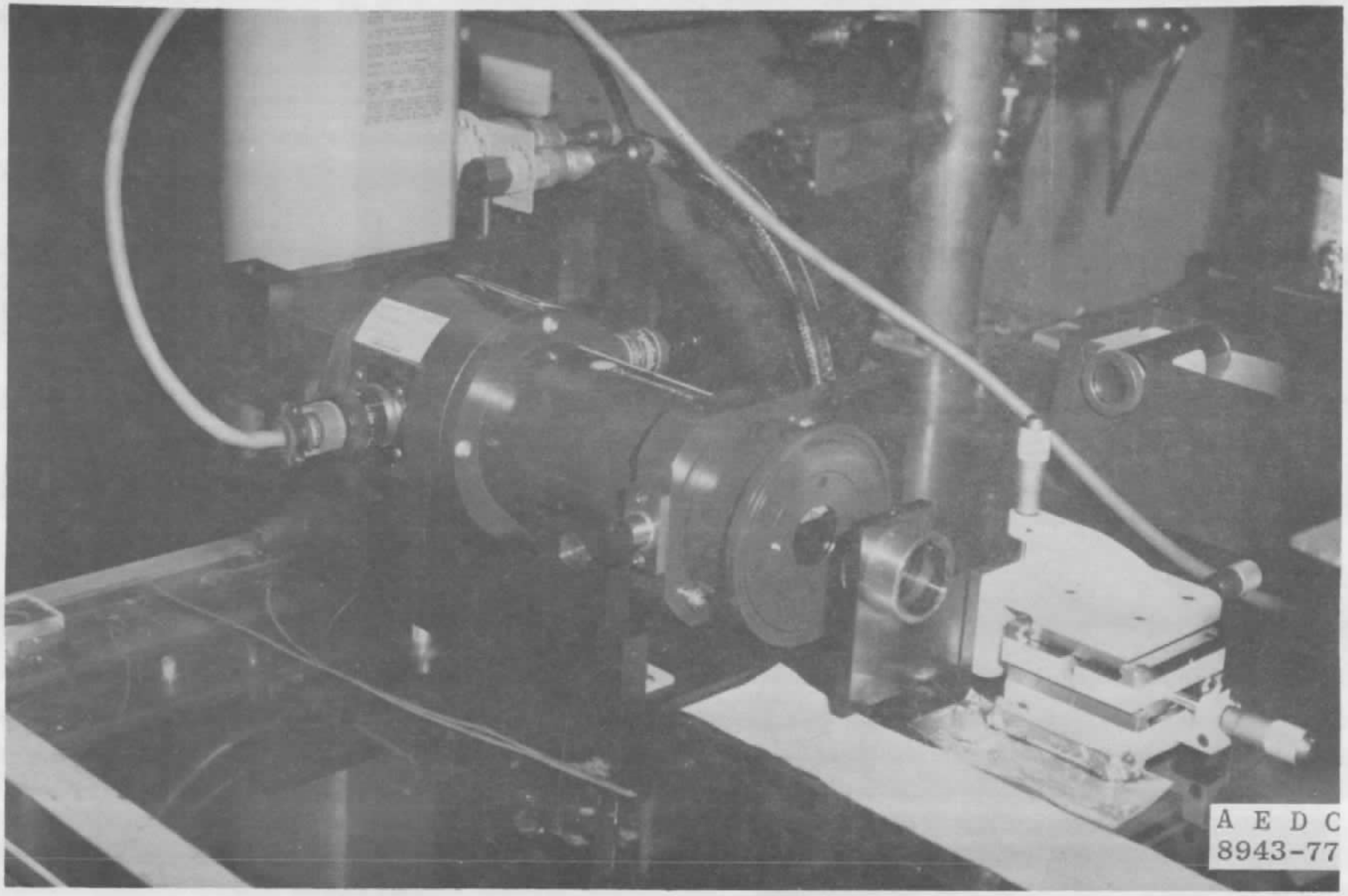


Figure 5. Photograph of the cold head and lens.

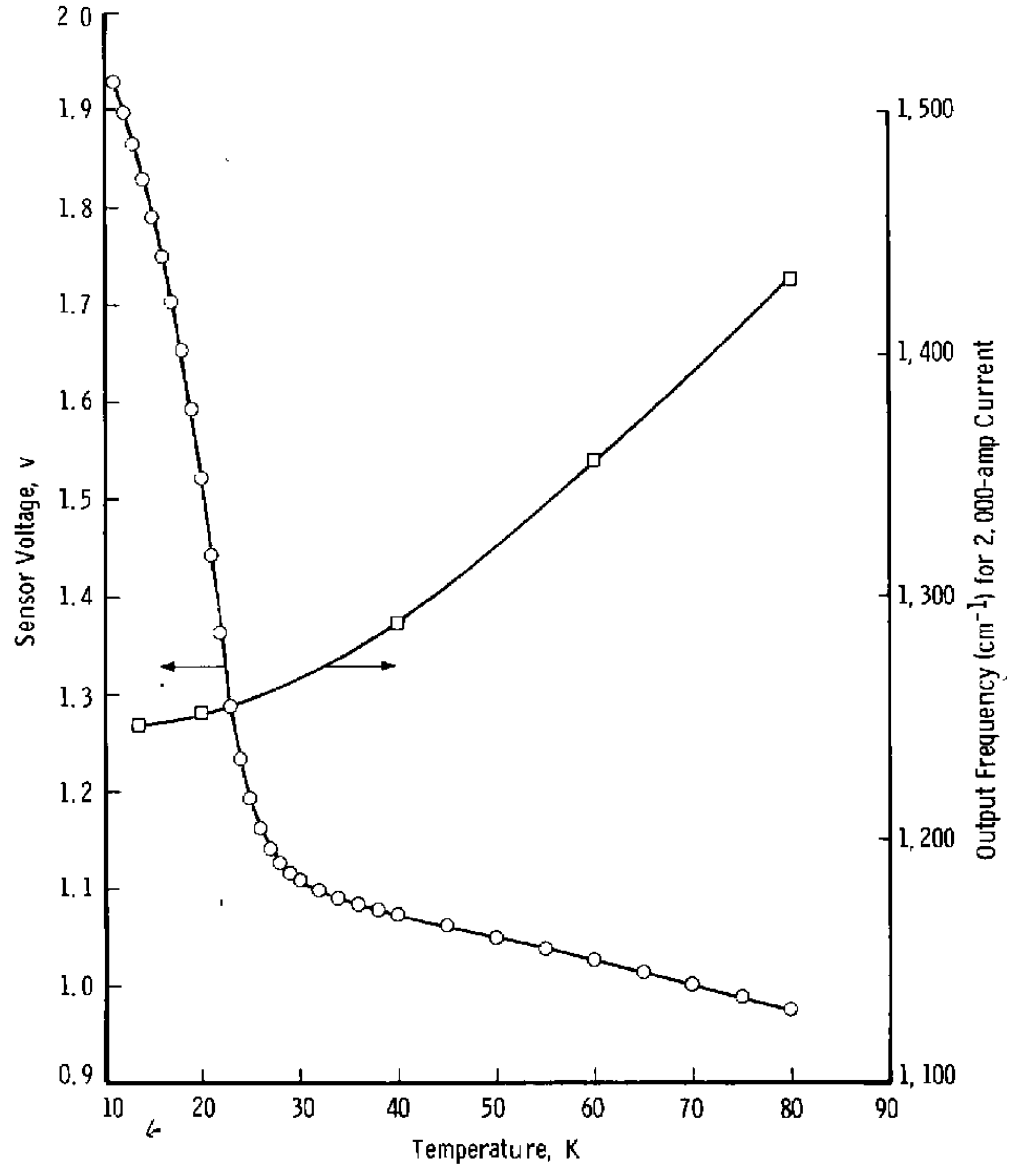


Figure 6. Sensor voltage and diode laser frequency versus temperature.

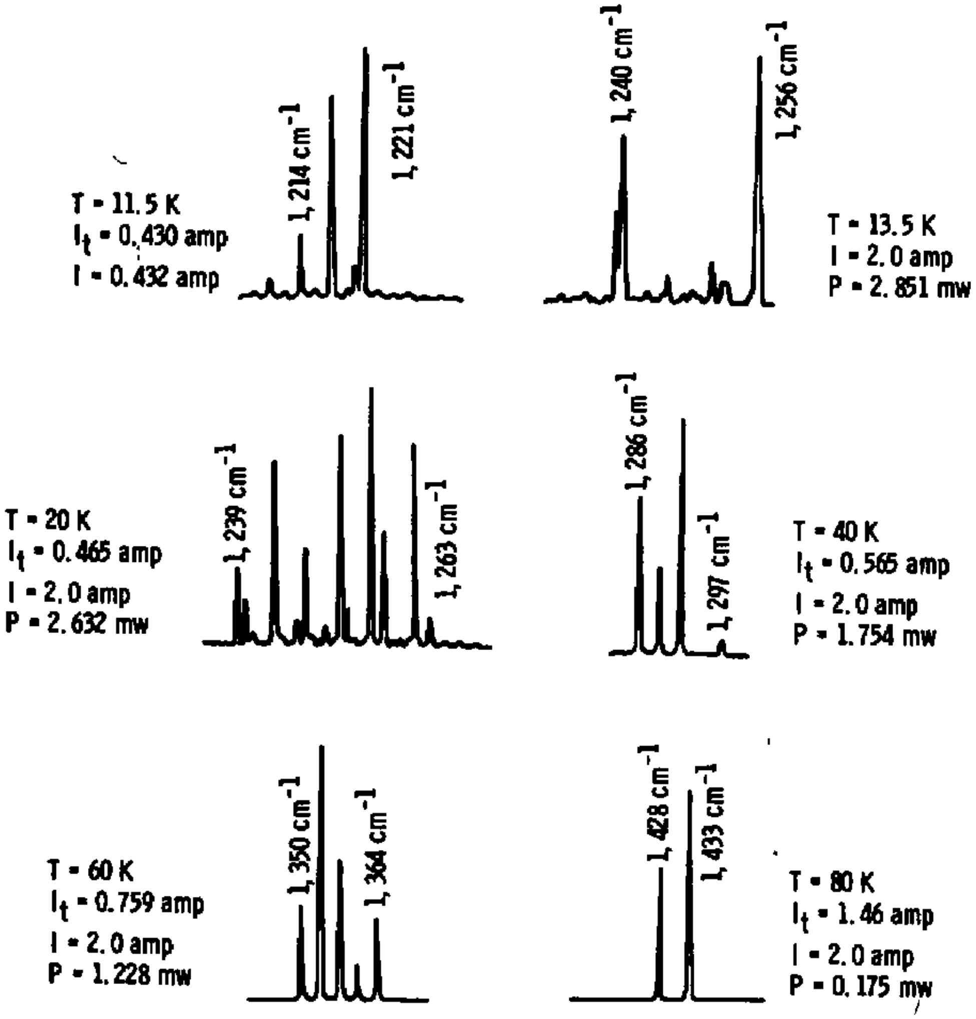


Figure 7. Spectral scans of the diode laser emission at various temperatures.

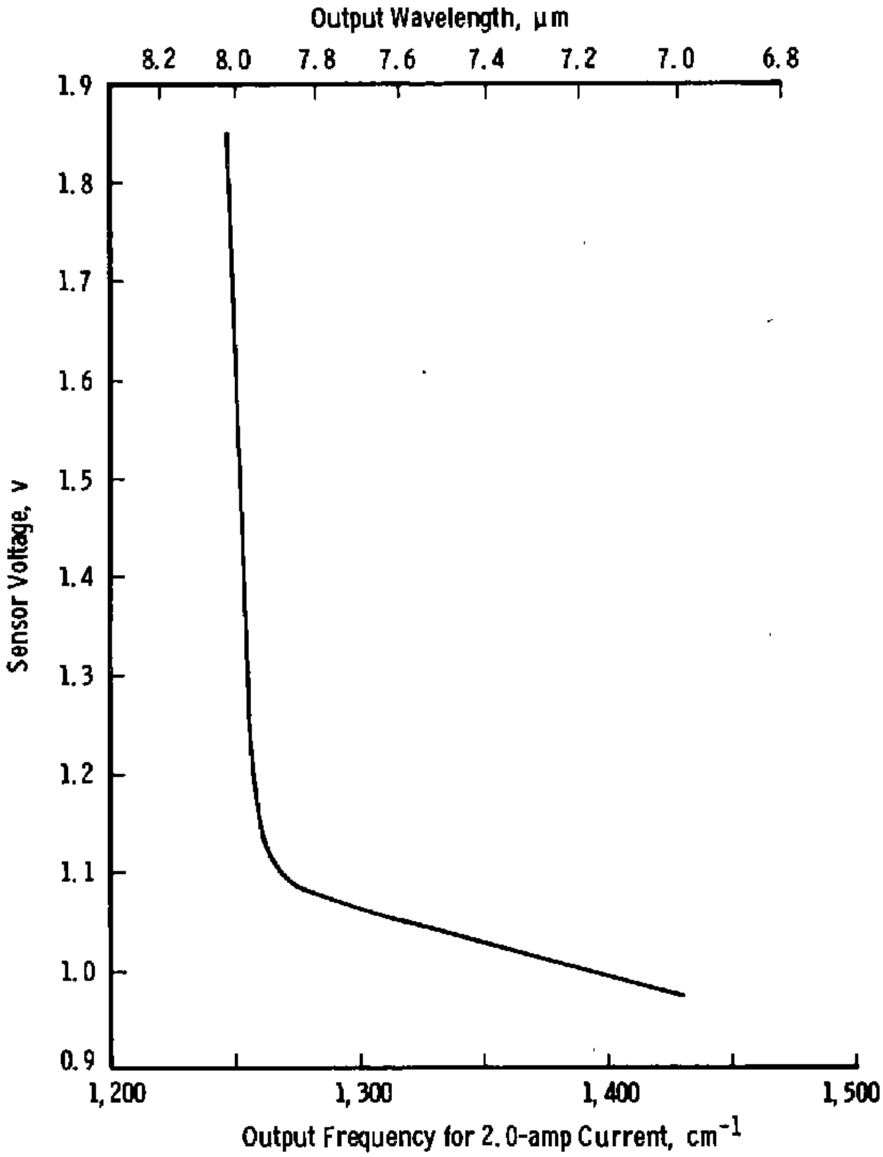


Figure 8. Output frequency and wavelength versus sensor voltage.

Evaluation of the unknown diode laser parameters was carried out with the aid of a low-pressure methane (CH_4) gas absorption cell. Absorption lines of the ν_4 fundamental band of methane were observed and photographed on an oscilloscope through the use of the LCM sawtooth current modulation; in this mode repetitive diode laser current sweeps were synchronized with the horizontal time sweep of the oscilloscope. Identification of methane and water absorption lines were positively made by using the information of Refs. 5, 6, and 7. Amplitude and wavelength stability and repeatability checks on the same group of lines were made throughout the evaluation period. The behavior of individual modes could also be determined by the observation of those lines.

Oscilloscope photograph numbers 2 and 7 in Fig. 9, in which the depth of an absorption line is a function of the mode amplitude, show how a mode amplitude can change with a slight change in excitation conditions. Note that an additional absorption line in photo number 7, which does not belong to the normal spectrum of photo number 2, is produced by a different mode whose frequency is absorbed by a different absorption line during the same current sweep range. Photograph numbers 5 and 9 of Fig. 10 were made on different days and illustrate the same type of change. In contrast to the resolution of Ref. 5, lines 35 and 36 are completely resolved, and the natural absorption linewidth at this pressure is still much greater than the linewidth of a single diode laser mode. The spectrum of Fig. 9 is repeated in Fig. 11 at four currents but at constant sensor voltage and amplitude sensitivity. This shows that at least four different modes may cover the same frequency range at this temperature. Shown in Fig. 12 are two identified water vapor absorption lines: ambient air (methane cell removed), and water vapor as an impurity in the low-pressure methane cell.

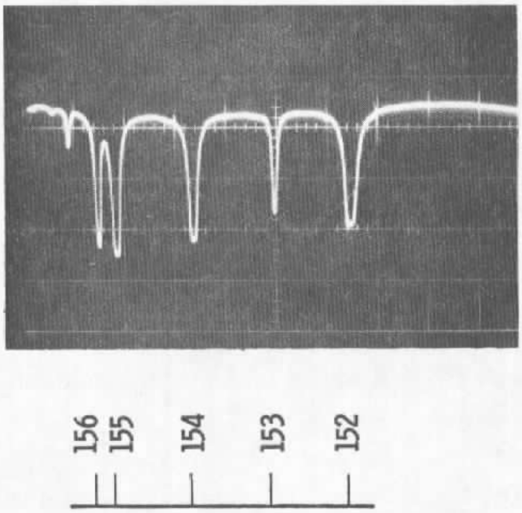
The amplitude and wavelength stability of any mode were excellent when the system was allowed to operate unattended. After a major temperature excursion, however, it was often difficult to find the same absorption line spectrum; that is, the particular mode's power output and/or wavelength would not be the same as before. The changes worsened as the system was activated upon subsequent days. Although it was not possible, it would have been very interesting to spectrally scan the mode pattern after such a temperature excursion for direct observation of these changes. The output power of each mode is variable throughout its tuning range and typically peaks near the middle of the range. No definitive data were taken to measure the reproducibility of the power curve, but it is suspected that significant changes do occur that are related to the observed wavelength changes. In the region of plentiful, known wavelength absorption lines, it appeared to be possible to adjust the current and temperature to obtain any desired wavelength; that is, no appreciable wavelength gap existed, but it was not possible to determine whether this was true for all spectral regions.

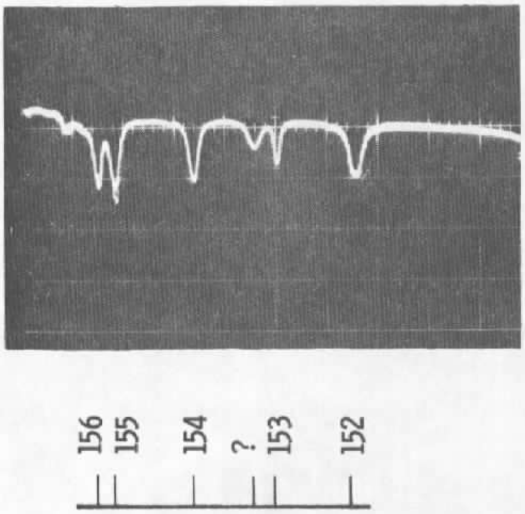
Photo No. 2

2v/cm Amplitude
1.0609 Sensor Volts
1.3450 amp

Photo No. 7

2v/cm Amplitude
1.0604 Sensor Volts
1.3145 amp





Line Number	Frequency (cm^{-1}) According to Ref. 5
152	1,304.223
153	1,304.332
154	1,304.463
155	1,304.602
156	1,304.663

Figure 9. Spectral scans of methane at slightly different conditions.

Photo No. 5

1v/cm Amplitude
1.6188 Sensor Volts
1.7038 amp

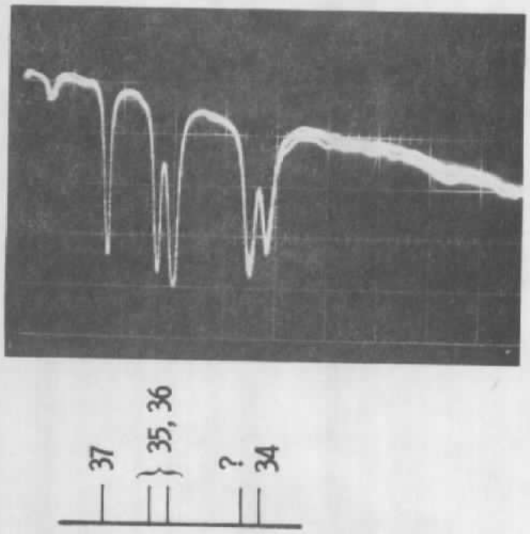
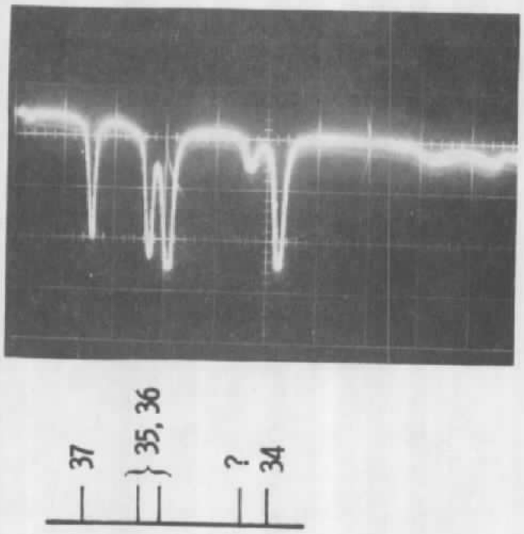


Photo No. 9

2v/cm Amplitude
1.6188 Sensor Volts
1.6898 amp



Line Number	Frequency (cm^{-1}) According to Ref. 5
34	1,247.703
35, 36	1,247.827
37	1,247.903

Figure 10. Spectral scans of methane on different days.

Photo No. 12, 1.9292 amp

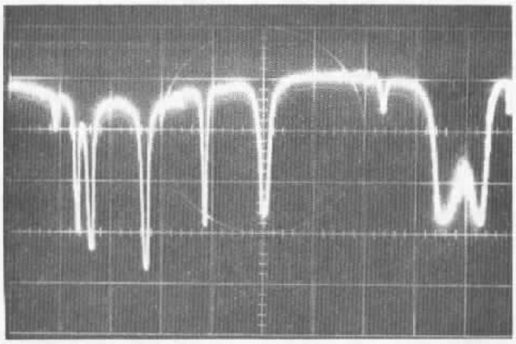


Photo No. 13, 1.6500 amp

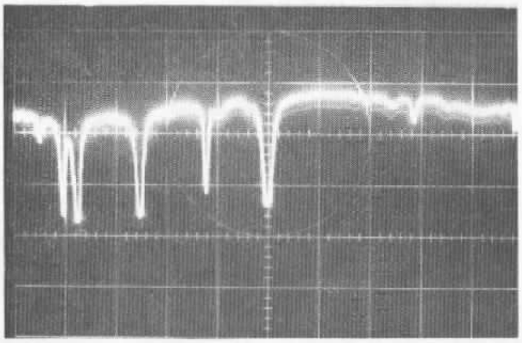


Photo No. 14, 1.3247 amp

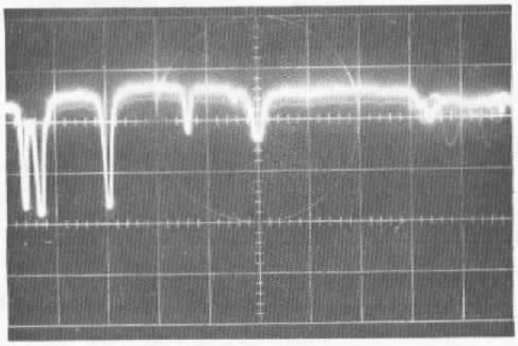


Photo No. 15, 0.8372 amp

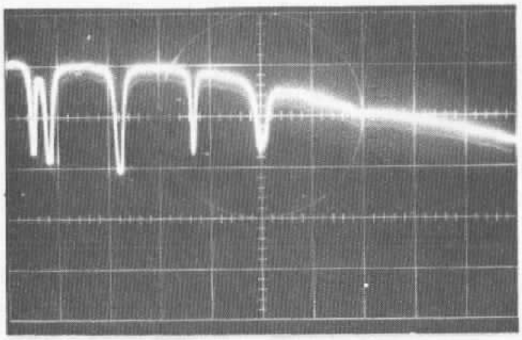
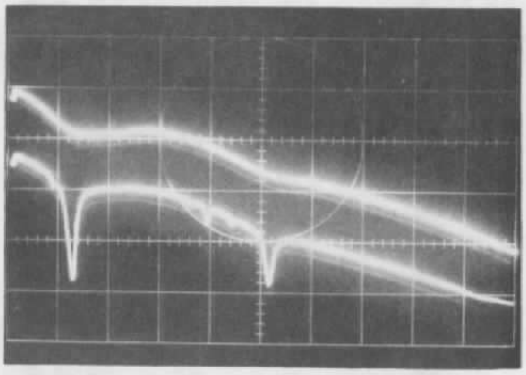


Figure 11. Spectral scans at 1,304 cm^{-1} and a sensor voltage of 1.0585 v.

Photo No. 11

1.0200 Sensor Volts
0.9373 amp



Top Trace: Methane Cell Removed
Bottom Trace: Methane Cell in Optical Path
Left Absorption Line: Line 8 of Ref. 7, 1,363.2628 cm^{-1}
Right Absorption Line: Line 7 of Ref. 7, 1,363.0612 cm^{-1}

Figure 12. Spectral scans of methane cell low pressure H_2O and atmospheric water.

Tuning rates of the diode laser system were measured in the stepped and continuous modes. The time required to change a known wavelength step was readily measured. In a continuous mode the diode was allowed to cool down from 80 K in such a manner that the total wavelength range was scanned in a known time interval, and the results are shown in Table 8. Rates over only about one cm^{-1} can be widely controlled by the LCM. The laser diode power output was measured by the manufacturer at five temperatures and 2.0 amp, and the oscilloscope output voltage was recorded at 1.95 amp over the temperature range, and both are plotted as a function of wavelength in Fig. 13. The AEDC measurements

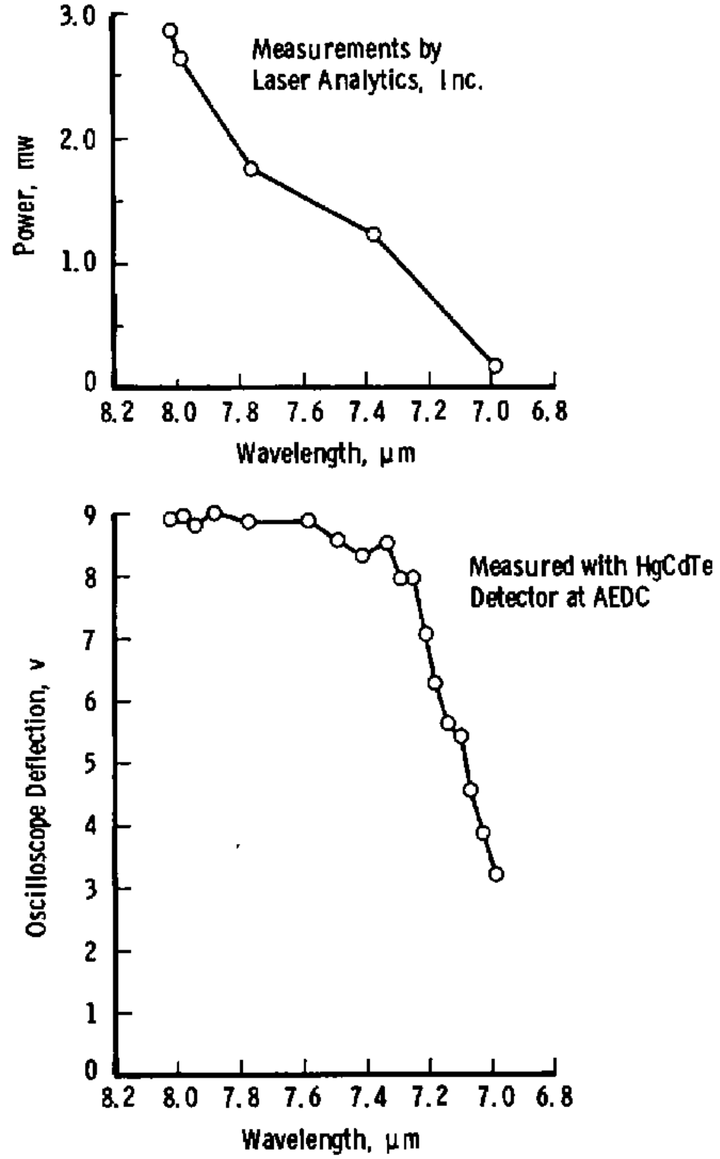


Figure 13. Diode laser power versus wavelength.

would require correction as a result of the wavelength-dependent transmissions of the doublet lens and cold-head window, and of the HgCdTe detector. Typically, the sensitivity of the detector is peaked near 7.6 μm, and the shape of the manufacturer's curve is obtained with the application of this correction alone. Rectangular slits of various dimensions were placed near the focusing lens for examination of the beam's spatial properties. All the characteristics of this diode laser are summarized in Table 8.

Condensation on the cold-head KRS-5 output window was observed two weeks after the system was evacuated, and it was then necessary to warm tne cold head and re-evacuate it. The rise in pressure was in correlation with a gradual rise in the lowest temperature obtainable with no diode laser current.

Table 8. Summary of Diode Laser Characteristics

Spectral Range: 1,214 to 1,433 cm^{-1}, or 8.24 to 6.98 μm

Temperature Range: 11.5 to 80 K (As temperature increases, wavelength decreases.)

Current Range: 0 to 2.0 amp (As current increases, wavelength decreases.)

Passband/Mode: $<10^{-4}$ cm^{-1} or $<10^{-6}$ μm

Number of Principal Modes: 2 to 10 (See attached spectra.)

Mode Separation: $\sim$1 cm^{-1} or $\sim$0.005 μm

Total Passband: 5 to 25 cm^{-1}, or 0.03 to 0.15 μm

Spectral Range/Mode: $\sim$3 cm^{-1} or $\sim$0.017 μm

Number of Modes Required to Cover Total Spectral Range: $\sim$80

Total Mode Power: 2.8 mw at 8 μm to 0.18 mw at 7 μm, with Only = 3 percent Sudden Power Change as Modes Switch

Power/Mode: Variable (Each mode's power curve is different.)

Tuning Rate a) Continuous Mode

1) Temperature Change Only: diode allowed to cool from 80 K - cover total λ range in 18 minutes, or average of 0.0012 μm/sec.

2) Current Change Only: repetitive scan by Laser Control Module - 10^{-4} to 10^{4} cm^{-1}/sec or 10^{-6} to 10^{2} μm/sec over $\sim$1 cm^{-1} or 0.005-μm range.

b) Stepped Mode

1) 0.01 μm steps: 1 min/step in either direction.

2) 0.1 μm steps: 3 min/step while decreasing wavelength, 8 min/step while increasing wavelength.

Wavelength Stability: Within 0.01 cm^{-1}/hr or 5×10^{-5} μm/hr

Wavelength Reproducibility: In One Week, Within 0.3 cm^{-1} or 0.002 μm

Amplitude Stability: <0.5 percent Typical

Amplitude Reproducibility: Within 6 percent (all of the variation found could have been due to the detector.)

Collimation: 90 percent of the power is Radiated Within a Half Angle of 12 deg

5.0 SUMMARY

A summary of the performance of the diode laser which was studied is given in Table 8, and a comparison of the features of this type of source with a source using the difference-frequency generation method is given in Table 9. The characteristics of the difference-frequency method are based on literature references, knowledge of the pertinent equations of the technique, and judgement of the difficulty of its implementation.

Regarding the diode laser source and the comparison of its performance with the desired source characteristics which were listed in an earlier section, several of the disadvantages listed in Table 9 are crucial. First, the desired wavelength tuning rate of approximately 0.005 μm/sec obviously is dictated both by requirements concerning the time necessary to accomplish a complete spectral scan and by chamber occupancy time restrictions. For the diode studied, the tuning rate was approximately 0.001 μm/sec, which is significantly less than desired; further, it should be noted that the wavelength range covered was approximately 2 μm. The time required to change the diode sources to extend the wavelength coverage to the entire desired spectral range will reduce even further the effective diode tuning rate, and an order of magnitude difference between desired and achieved parameters appears likely. Second, the number of diodes required to cover the desired spectral range listed in Table 1 can be determined approximately from the information supplied in Table 6. Depending upon exactly which diodes are selected for coverage of the 3- to 30-μm region, the number of diodes required exceeds thirty; the expense of such an approach is high. Clearly, more limited spectral regions can be scanned with fewer diodes and reduced cost. However, the strategy of a limited capability source selection and its resulting cost effectiveness was not the purpose of this study; consequently, no further discussion will be presented concerning this point.

Table 9. Infrared Source Performance Summary

System	Advantages	Disadvantages
Diode Laser	Overall Wavelength Range Possible Narrow Passband (Monochromatic) Stable, Reproducible Excellent Wavelength Calibration Physically Compact	Number of Diodes Required is Large Slow Tuning Rate No Dynamic Range Expensive System
Difference Frequency Generator	Overall Wavelength Range with 1 - 2 Crystals Narrow Passband Good Dynamic Range Fast Tuning Rate Excellent Wavelength Calibration	Significant Development Required Physically Large Expensive System

The desired or required passband or spectral width of the source is shown in Table 1 to vary with source wavelength, but a rule-of-thumb wavelength width of 0.1 μm is adequate. The diode source demonstrated a superior linewidth quality, particularly if single-mode output was used. In addition, one should note that for a given wavelength setting with this particular diode, without single-mode selection the wavelength width was on the order of 0.03 to 0.15 μm, which, in the main, is acceptable. However, the use of a single mode is not recommended because of the mode structure changes which occur on tuning; i.e., mode structure reproducibility, which is a necessity, is not achieved. Since this alternative is precluded, it is reasonable to consider the multimode output, which, though broader than single mode, is, for the most part, acceptable in spectral width. Unfortunately, this, too, appears to be unfeasible, for not only is the mode structure quite sensitive to excitation conditions, the multimode power output and possibly reproducibility are also critically dependent on these conditions. A review of Fig. 11 will demonstrate the validity of this assertion. Therefore, neither single- nor multi-mode operation of this type of source appears to be acceptable for broad wavelength scans.

As a final negative comment, the absence of an inherent dynamic range of the output power is a significant disadvantage, particularly when one notes that ten orders of magnitude range is desired. It is possible that a substantial fraction of this desired dynamic range can be achieved by clever attenuation techniques. To be frank however, ten orders of magnitude exceeds the anticipated level of cleverness.

In summary, even though the diode laser source offers distinct advantages in that its power output is acceptable and it is both compact and convenient to operate, the negative aspects of its performance with respect to the desired source characteristics are most significant. Therefore, it is recommended that the diode laser source not be pursued further as a general calibration source for sensor testing. It is noted that special, narrow-band test and research requirements may be best satisfied by the use of diode sources, but such applications were not of concern for this work.

It is recommended that a similar study be performed for the difference-frequency generation technique to evaluate its applicability for such test purposes.

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NOMENCLATURE

A	Area
c	Speed of light
d	Grating constant
di	Equivalent slit width in angular measure
E	Diode energy gap width
H	Characteristic source dimension
h	Planck's constant
I	Diode current
I_t	Diode threshold current
$\hat{I}(\lambda)$	Power spectral density at wavelength λ
i	Angle of incidence
L_ℓ	Longitudinal coherence length
L_t	Transverse coherence length
ℓ	Laser cavity length
m	Integral number of half-wavelengths within laser cavity
m'	Diffraction order
n	Index of refraction
P	Power
$\hat{P}_\lambda$	Spectral flux density, or radiant emittance, at wavelength λ
R	Ratio of spectrometer focal length to slit length
$S(\lambda)$	Power transmitted by spectrometer at wavelength setting λ

T	Temperature
$\Delta\lambda$	Bandwidth
λ	Wavelength
θ	Angle subtended by source